Processes Controlling Transfer of Fine-Grained Sediment in Tidal Systems Spanning a Range of Fluvial Influence

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Award Number: N00014-10-1-0213; N00014-12-1-0181
http://tidalflats.org

LONG-TERM GOALS

A long-term goal of our sediment transport and deposition investigations is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. The general aim of this project is to investigate how forcing processes affect the sediment-transport dynamics that act to import or export fine-grained sediment in shallow-water regions with fine-grained sediment supply. We strive to understand how the delicate balance of ebb and flood sediment fluxes is maintained to create tidal flat and mangrove complexes, and distributary shoals and islands within tidal rivers. All of these environments are characterized by variable bathymetry and variable seabed stability, and our goal is to answer the question: How do the processes that control the transfer of fine-grained sediment, e.g., tidal (semidiurnal, fortnightly), riverine and other seasonal (winds/waves, precipitation temperature, and biological) processes influence the transport pathways, seabed erosion/deposition, and morphological development in shallow tidal systems?

Understanding the transfer and transformation of sediment between terrestrial source and marine sink is essential for knowledge of global carbon budgets, landform evolution, and interpreting the stratigraphic record. Sediment is eroded, transported, and trapped via a myriad of processes along the continuum from terrestrial to oceanic environments. These processes are driven by the varying degrees of fluvial, wave, and tidal influence in each environment. At present, we are completing our studies on unvegetated tidal flats, and are ramping up our focus on sedimentary phenomena in relatively unstudied components within the source-to-sink framework: the connection between the tidal river and the subaqueous delta on the inner continental shelf, and sediment sinks within vegetated/mangrove shoreline complexes. Our overall hypothesis is that sediment-transport signals (magnitude, grain size, pathways) are modulated within the tidal river and tidal floodplains before the delivery of sediment to the continental shelf, and thus processes in these regions exert a control on the ultimate fate of sediment particles.

OBJECTIVES

This research is designed to investigate sources and sinks of sediment in the tidal river and intertidal areas of the overall source-to-sink system. To address our objectives we use data collected as part of the Tidal Flats DRI and preliminary results from the Tropical Deltas DRI on the Mekong River, along

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2012**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Processes Controlling Transfer of Fine-Grained Sediment in Tidal Systems Spanning a Range of Fluvial Influence**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **School of Oceanography Box 357940 Seattle, WA 98195**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

with results from the Amazon River delta system that are guiding our efforts. Our objectives focus on the following three areas:

1. **Channel/Flat Sediment Transfer on Unvegetated Tidal Flats** (e.g., Willapa Bay and Skagit Bay, WA). Here we examine processes that transfer fine-grained sediment within and between the flat surfaces and the channels that incise them. We have investigated the general characteristics of channel/flat water and sediment discharge and also the external stresses (e.g., winds, precipitation, and river discharge) that modify these processes. Water and sediment flux of the system have been evaluated and the dynamics of short-lived velocity pulses examined.

2. **Transport Pathways in the Tidal River**. In many large rivers the tidal reach is largely unstudied, and the sedimentary dynamics within them control the magnitude and routing of particles onto the continental shelf. We hypothesize that there are mutually exclusive pathways for sediment on flood and ebb tides that control the deposition of sediment into distributary islands, impact the storage and release of sediment in both the main stem and floodplain areas, and alter the delivery mechanisms to the continental shelf, thereby placing a controls on sediment fate.

3. **Sediment Retention and Release on Mangrove/Vegetated Intertidal Areas**. Along the main stem tidal river and in the offshore banks may be shorelines lined with vegetation (mangroves at the seaward fringe and other brackish-water vegetation in the fresher reaches). We explore the role of the tidal channels in routing sediment to and from the tidal floodplains, and contrast these processes to those investigated in previous studies of unvegetated intertidal regions.

APPROACH

We use in situ observations to evaluate the hydrodynamics, sediment fluxes, and sediment characteristics within the range of tidal/fluvial environments listed above. Data from instrumented tripods and boat-mounted platforms deployed in the main stem of distributary river channels, in tidal channels of different size and on adjacent flat intertidal surfaces allow us to investigate the hydrodynamics and sediment dynamics of each morphological setting. We determine water and sediment fluxes and evaluate the importance of meteorological forcing in these dynamics. In addition, we strive to work with other investigators to enhance modeling and remote sensing efforts, and to develop an overall understanding of the system dynamics.

Channel/Flat Sediment Transfer on Unvegetated Tidal Flats:
Our work under the Tidal Flats DRI has focused on the processes controlling the transfer of fine-grained sediment within and between channels and flats on two contrasting meso-tidal flat environments. The primary study site is in Willapa Bay, a muddy embayment in SW Washington that is tidally dominated and receives relatively little direct freshwater influence. This study area allows us to focus on asymmetries in tidal processes. In comparison, the secondary study site on the Skagit River tidal flats (NW Washington) has similar tidal and wind forcing, but in addition has a large river input of freshwater and sediment resulting in a seabed dominantly composed of sand. Approach and results are contained in the publications: Nowacki and Ogston (2012); Webster et al. (in press); Boldt et al. (2012); Hsu et al. (2012).

Transport Pathways in the Tidal River
We investigate water and sediment fluxes in the tidal river by surveying transects over complete 24-hour tidal cycles and deploying time-series instrumentation over the fortnightly cycle. During August

2012 a preliminary investigation was conducted on the Song Hau distributary of the Mekong River in the region where the tidal river separates around Cu Lao Dung Island (Fig. 1), and from this data, we are establishing a set of transects to be reoccupied in future field efforts. In this preliminary effort, we undertook spatial surveys of the river distributary around the island (shown in Fig. 1) and after evaluating this data, we focused on transects: A) around small distributary islands at the north end of Cu Lao Dung; B) a cross-section at the northern end of the island that was strictly a tidal river (freshwater, but reversing flows); and C) a cross-section towards the southern end of the island where we observed salt water intrusion over a short portion of the tidal cycle. The boat transited for 24 hours across the channels at locations B and C, in order to delineate semi-diurnal variations in fluxes. We continuously operated an ADCP to measure current velocities, backscatter and bathymetry. We also used a CTD with OBS, and suspended-sediment samples were collected for calibration of the ADCP backscatter and OBS, and these water samples also will be used to investigate suspended-sediment grain size and extent of flocculation.

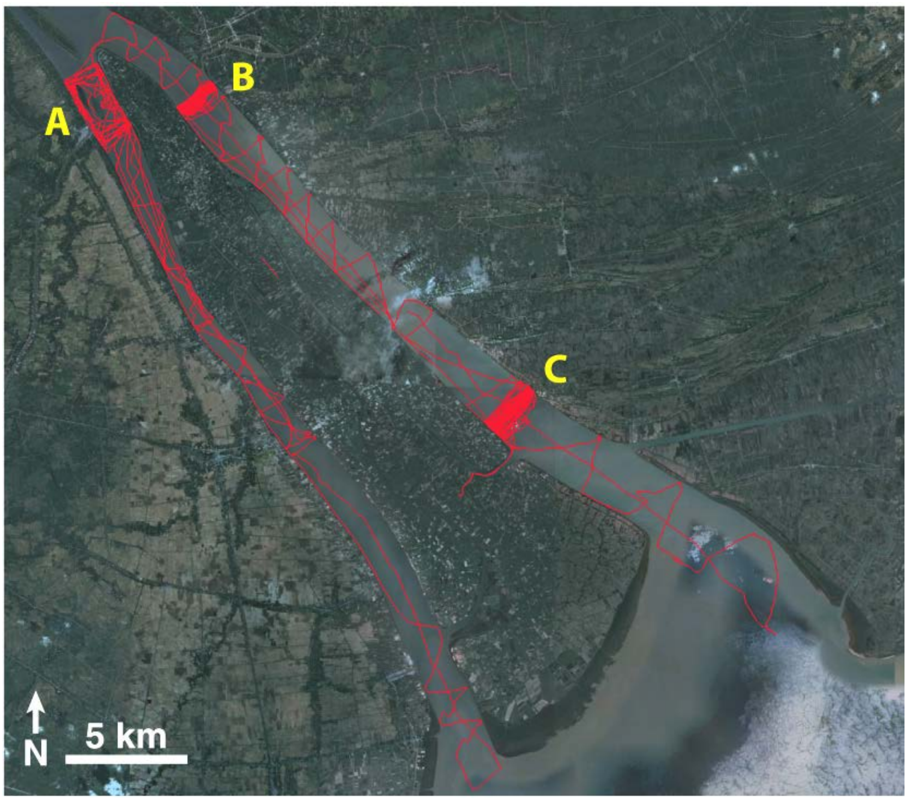

Figure 1. Tracklines of the spatial survey of bathymetry, currents, water-column structure, and suspended-sediment concentrations around Cu Lao Dung island in the Song Hau distributary of the Mekong River.

Analysis of the along-beam distance to the boundary of each of the four ADCP beams allows the generation of a detailed picture of the bottom depth. This provides a patch of across-distributary bathymetry (in addition, a digital depth recorder was used continually while underway) as hourly transects can be sited at a small distance apart (Fig. 2). This method of determining bathymetry has and will be operated during all operations (e.g., along and between transects; during travel to mangrove and freshwater intertidal channels), and will provide spatial information about bathymetry and a

glimpse of bottom bedform structures. We plan to combine data sets with other investigators undertaking seabed studies focused on bed sediment composition to understand the processes and resulting morphologies within the tidal main stem.

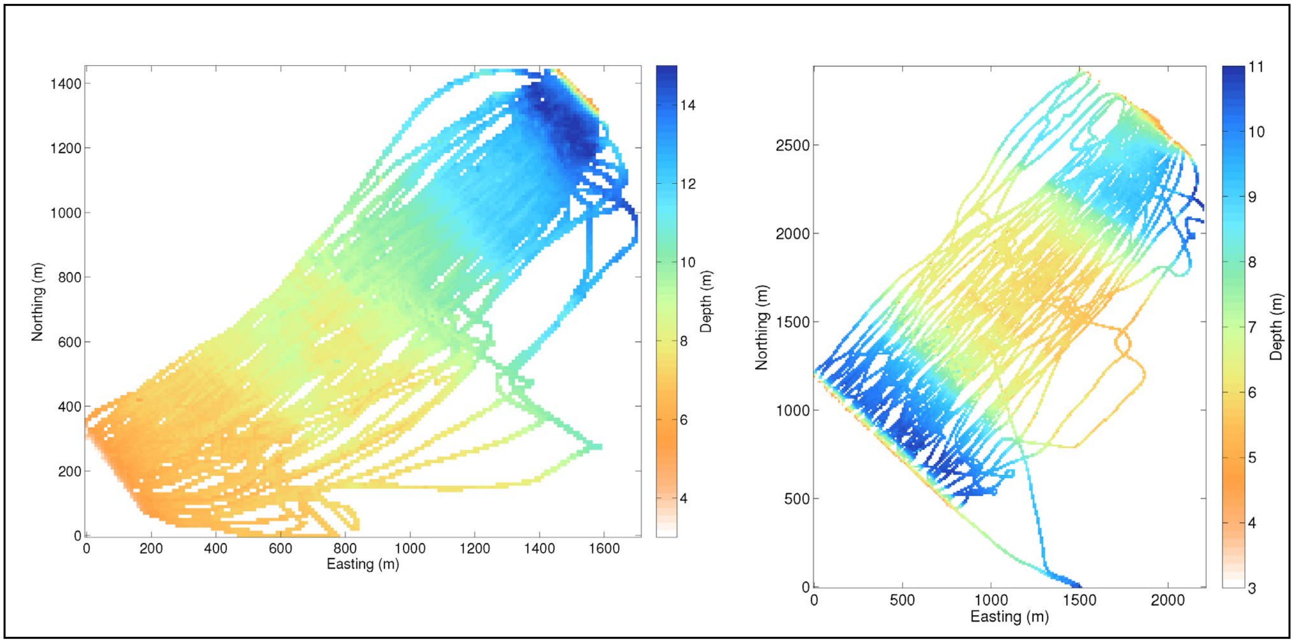

Figure 2. ADCP bottom tracking can be processed during 24-hour transect studies to obtain detailed bathymetry. The left image of bathymetry is located at the northern end of Cu Lao Dung island (B in Fig. 1), and the right image is located at the southern end (C in Fig. 1).

All of the transects will be studied during both neap and spring conditions, with the purpose of documenting semi-diurnal and fortnightly tidal asymmetries. We plan to address the evolution from tidal river dynamics to estuarine dynamics as it relates to the sediment transport and budget through the tidal river. During high-flow conditions, as was the case in August 2012, the upper transect (B) was predicted to be entirely freshwater, and the lower transect (C) was predicted to be at the edge of the estuarine processes (Wolanski et al., 1998; Mekong River Commission, 2005), and this was seen to be true. During high-flow conditions, the upper transect should also be near the maximum upriver extent of the turbidity maximum, providing a contrast of conditions over the annual cycle.

Sediment Retention and Release on Mangrove/Vegetated Intertidal Areas
Instruments (e.g., Aquadopp high-resolution current profiler and OBS) will be deployed on the bed near the entrance of vegetated tidal channels located within various reaches of the tidal distributary to monitor fluxes throughout the neap to spring transition. This is an approach that has been proven in studies of Willapa Bay (Nowacki and Ogston, 2012) and Amazon tidal channels (Nowacki et al., 2012). In addition, CTD/OBS observations will be made throughout the survey period to document water-column stratification of salinity and suspended sediment. Our focus with these studies is on exchange between the main stem and the tidal floodplain. There are a vast number of channels that incise the Mekong tidal floodplain, and we plan to investigate their role in storing sediment. Preliminary work has revealed that these channels ultimately meld into the floodplain and may serve as effective conduits for importing or exporting sediment.

We will investigate questions that include: What are the processes by which tidal floodplain channels serve to import or export sediment over hourly to weekly time scales? Results from preliminary investigations in several tidal channels along the Amazon tidal river show some intriguing processes at work that are relevant to sediment transport to the tidal floodplain. Thermal fronts appear to be a significant factor in importing sediment upstream. A turbidity maximum resulting from flow convergence is an important part of this process. We seek to answer questions including: What are the timescales of heating and cooling in the tidal floodplain, and how does the thermal front process vary during daytime and nighttime tidal cycles? How important is the thermal turbidity maximum to the overall sediment budget? Are gravity currents, produced by buoyant, warm river water, important to the flow regime?

WORK COMPLETED

During the year covered in this report, the emphasis on the Tidal Flats DRI studies has been on data analysis, integration of results, and publication. Four manuscripts have been accepted for publication to a *Continental Shelf Research* special issue on Tidal Flats. These papers will be published 2012. Two more manuscripts are in preparation.

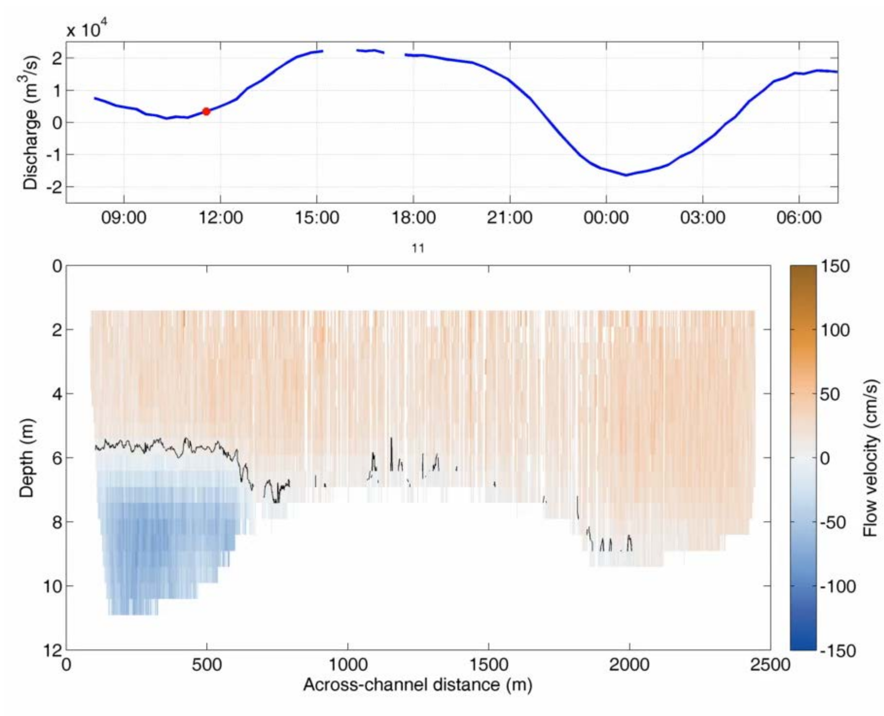

Figure 3. Example transect of flows in the Song Hau distributary of the Mekong River. The upper panel shows the water discharge through the cross section over a 24-hour period, and the lower panel shows the flow velocity at approx 11:00 am, during a lesser flood tide. Note the "mutually evasive" channelization of flooding river flow on the west side of the section.

In addition, we have undertaken an initial data collection effort in the tidal Mekong River. Much of our effort on the Tropical Deltas DRI has been in developing relationships with Vietnamese colleagues and traversing the path through their political, cultural and scientific systems to allow us to undertake

our joint field effort. The initial field campaign was conducted between 20 August and 2 September 2012, and provided intriguing preliminary data for the overall Tropical Deltas DRI, and a greater understanding of the pathways necessary to do scientific research in this region.

The data collected in this initial phase of the program included 1) spatial surveys of ADCP/CTD/SSC in the Song Hau distributary of the Mekong River on both the east and west sides of Cu Lao Dung island (Fig. 1), 2) 24-hour transects of the main stem of the river channel in two locations – one with salt-water intrusion, the other 30 km upstream in the completely fresh, but reversing tidal river, and 3) focused transects around small deltaic islands within the main distributary. In addition, a pressure sensor was deployed at a fixed site throughout the time period of our focused transects.

RESULTS

The research effort on unvegetated tidal flats has resulted in numerous presentations, four in-press publications, and two more manuscripts in preparation. Our investigations of both muddy and sandy flats (Willapa Bay, WA and Skagit Bay, WA, respectively) highlight the dynamics and processes that can be compared and contrasted between these systems. On muddy flats, dynamics of the velocity pulse when water level in channels approaches the surrounding flat elevation are modulated by seasonal and meteorological conditions, and on average, this pulse comprises 35% of the suspended-sediment transport (Nowacki and Ogston, 2012). In addition, processes at the water's edge as it progresses across the flat surfaces over the tidal cycle actively resuspend sediment and contribute to the landward net sediment fluxes (Hsu et al., 2012). Rain falling directly on unvegetated flats causes significant erosion, and strips the flat seabed surface, temporarily depositing sediment in channels (Nowacki and Ogston, 2012). Although there are significant seasonal changes in seabed properties, the imposed bed stresses are relatively consistent over time (Boldt et al., 2012). In contrast, on sandy flats with significant river discharge much of the riverine fine-grained sediment is rapidly exported from the tidal flat system, and the small amount that does deposit on the sandy flats is subsequently reworked and removed by wave-ripple migration on the flat surfaces (cm), unidirectional bedform migration within the channels (cm to 10s of cm), and channel migration within the braided channel network (m) (Webster et al., accepted).

Our work in the tidal river and vegetated shorelines of the Mekong Delta is in its beginning exploratory stages. Initial work includes an evaluation of the flood/ebb dominance within and between distributary channels in relation to the deltaic islands and shoals (looking for "mutually evasive" flow, Harris et al., 2004; Fig. 3). In addition to the flow, we are investigating the pathways and fluxes of sediment in the main distributary channels throughout the tidal cycle. Transects of water-column currents and suspended-sediment concentrations over complete tidal cycles along the tidal river show complex hydrodynamics and sediment dynamics within the main stem of the river (Fig. 3). We found that flow near the mouth is focused in the deeper side channels, particularly flooding flows in the western side where on lesser floods, the flow is highly sheared and has the characteristics of mutually evasive systems. Farther upstream, the channel is not symmetric, yet the flow appears focused in the shallower western side. The ADCP data can also be processed for bathymetry, and the intensive transect density allows us to develop patches of detailed bathymetry (Fig. 2). These data will be used to better characterize the seabed and its variability.

Preliminary results of studies in tidal rivers (i.e., Amazon River and Mekong River) reveal potential sediment trapping environments that include the tidal floodplain, which is incised by innumerable tidal channels; tidal freshwater "estuaries" at the confluence of large blackwater rivers and the mainstem of the river; mangrove forests at the salt-water extent of the system; and the bed of the tidal river itself. Relevant processes include barotropic tidal forcing and its interaction with fluvial discharge as well as baroclinic effects related to density differences produced by temperature and suspended-sediment concentration. Results from instrument deployments in small tidal channels allow us to quantify the role of these channels in the tidal-scale sediment budget of the vegetated floodplain and mangrove shorelines as well as identify the relevant sediment transport and trapping processes within the channels. We have not deployed sensors in Mekong River tidal channels yet, but have done a survey of candidate sites (Fig. 4). The tidal channels in the Mekong river system have been dramatically altered by humans, with nearly all the channels within the tidal river being controlled by constructed levees to protect fertile agricultural lands on the subaereal delta, and water and sediment fluxes are controlled by agricultural needs. As a guide and comparison for future studies on tidal channels in the Mekong, preliminary investigations in several tidal channels along the Amazon tidal river show some intriguing processes at work that are relevant to sediment transport to the tidal floodplain. Thermal fronts appear to be important in importing sediment upstream, and a turbidity maximum resulting from flow convergence appears to be a component of this process (Fig. 5). These preliminary results provide insight to the many unstudied processes active in tidal rivers worldwide, and are guiding our initial field efforts in the Mekong system.

Figure 4. An example of a tidal channel on the island of Cu Lao Dung. Channels are highly impacted by man -- most have man-made levees and some are actively dredged.

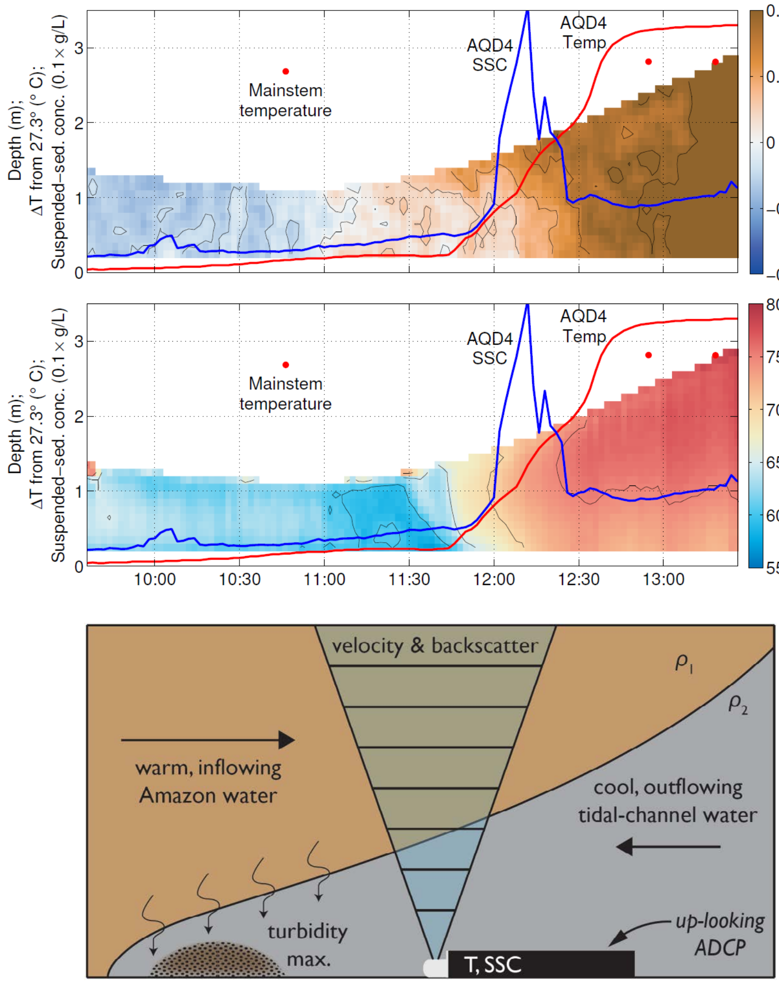

Figure 5. Example of data collected in a tidal channel of the tidal Amazon River, illustrating the suspended-sediment concentrations around a thermal front.

IMPACT/APPLICATIONS

Rivers are the largest suppliers of particulate material to the world ocean (Milliman and Meade, 1983), and the pathways that sediment takes in the transition from riverine to marine and the resulting water-surface expression can provide information about the bathymetry, shoreline processes, and ultimate fate of these particles. For the major rivers of the world, the gateways to the open ocean include the freshwater tidal reach, which can extend for hundreds of kilometers, and brackish to marine intertidal areas. The hydrodynamic and sedimentary processes in these environments remain poorly understood. Of particular interest are areas that temporarily store and release sediment such as tidal floodplains and the channels that incise them, deltaic distributaries and islands, and vegetated and unvegetated tidal areas. Understanding the processes in these environments, their impacts on mass budgets, and the most appropriate means to model and interpret remotely sensed observations of them requires research that is underway at present. Controls through the tidal river and tidal-flat gateways influence the signal propagation of sediment discharge from river to shelf environments. Where deltaic deposits are formed on the continental shelf, these controls should be detectable in the pathways and signatures of sediment flux and deposition.

The morphology and seabed properties of tidal flats and channels, tidal floodplains, and tidal rivers are linked to the mechanisms and rates of transport and deposition on the vegetated and/or unvegetated flats and in the channels that bisect them, and our studies aim to enhance the ability to predict these properties in other areas. Our studies also provide insight for coastal management that can be transferred to other tidal environments, allowing evaluation of the impacts of humans and invasive species on sediment dynamics.

RELATED PROJECTS

Although not directly a part of this program, a parallel study of tidal river and vegetated shorelines is underway in the Amazon River dispersal system. The mesotidal Mekong system has been intensely manipulated by mankind, and the Amazon system provides a contrasting large tropical deltaic environment that has had little anthropogenic modification. Comparison of processes across these two study areas allow us to quantify the effects of anthropogenic impacts.

An essential goal of the planned project is capacity building in the field of coastal and marine geology, and, in particular, estuarine and coastal sedimentary dynamics in Vietnam. The work we are undertaking will be adapted as other Vietnamese and US investigators become involved in the program. Particularly, we will adjust our efforts to accommodate needs of remote sensing studies and numerical modeling efforts. In addition, we plan to interact with ONR Physical Oceanography programs being conducted on the shelf relating to shelf/slope exchange as a function of monsoonal forcing. Their results will provide a broader context for our tidal river and nearshore studies, and we can provide more detailed information on the riverine/plume processes on the inner shelf.

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